History of Applied Superconductivity Research in China

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***Abstract*-The applied superconductivity research in China started in 1960s. Over the past 50 years, Chinese researchers have worked in many areas related to the applications and remarkable progress has been made. This paper presents brief historical account of events and Chinese achievements in three main areas of applied superconductivity research: large scale applications, materials and electronics.**

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I. INTRODUCTION

In 1959, liquefaction of He was successfully realized at the Institute of Physics, Chinese Academy of Sciences in Beijing. This marked the beginning of superconductivity research in China. From then on, research on the applications of superconductivity was gradually gaining momentum. The period of over 50 years may be divided into three phases. Prior to 1987, the research work activities were mostly limited to laboratory scale. The main work was towards developing superconducting wires and magnets, although research on electronic applications was conducted too.

Upon the discovery of high-temperature superconductivity (HTS), Chinese researchers made well known contributions and were among the first to synthesize materials with critical temperature, T_c, exceeding the liquid nitrogen temperature. This greatly promoted the superconductivity research in China: the Chinese government allocated a special budget for the HTS research. The National Center for Research and Development on Superconductivity was set up to guide and coordinate the research activity related to superconducting technologies in China. From 1987 to the late 1990's, the research funding for superconductivity was directed mainly towards HTS materials and focused on the fabrication and improvement of performance of

BSCCO-based tape conductors, ReBCO melt-textured bulks, thin films and Josephson junctions. Research on electronic applications was also carried out, including applications using HTS superconducting quantum interference devices (SQUID) and HTS microwave devices.

Since the late 1990s, the research funding in China has increased at a much faster pace than before, owing to the fast growth of the economy. Like other research areas, applied superconductivity research has received strong support from the government through a number of different programs such as the National High Technology Research and Development Program of China (863 projects), the National Basic Research Program of China (973 projects), projects funded by the National Natural Science Foundation of China (NSFC) and the Knowledge Innovation Program of the Chinese Academy of Sciences. Not only the number of research projects has increased, but also many large-scale application projects could be supported. The participation of China in the International Thermonuclear Experimental Reactor (ITER) project, the completion of the Experimental Advanced Superconducting Tokamak (EAST), the establishment of an HTS electric power substation and a demonstration base for HTS mobile telecommunications application are some of the examples. Overall, over the past 50 years remarkable progress has been made in applied superconductivity research in China. This paper presents a brief historical account of events in the three main areas of applied superconductivity research: large scale applications, materials and electronics. Needless to see, because of the large amount of work being performed during the span of over 50 years and because of the limited knowledge of the authors, it is impossible to cover all works in this paper. It is hoped that the paper will provide an overview on the progress of applied superconductivity research in China. Earlier published overviews of Chinese activities (in English) are listed in references [1,2,6,7,19,21,23].

II. LARGE SCALE APPLICATIONS

A. Superconducting Magnet Technology and Applications

In 1965, Professor Guan Weiyan of Institute of Physics, Chinese Academy of Sciences (CAS) worked together with Ge Wenqi and others from Wuhan Marine Electrical Propulsion research Institute to design and develop a 20 kW superconducting motor. The rotor coil was wound with single-core NbTi superconducting wires developed by Baoji Institute for Nonferrous Metals. This was the first superconducting magnet developed in China. In 1970, Zhang Chaoji and others of the Institute of Electrical Engineering and Li Zhishu and others of Institute of Physics, worked together to develop a superconducting magnetic energy-storage (SMES) coil with a maximum energy-storage capacity of 100 kJ, which was successfully applied in test as the laser power supply.

In 1970, Wang Kuiwu and others of the Southwestern Institute of Physics began to develop a superconducting magnetic mirror confinement apparatus for the research of nuclear fusion. It was made up of two superconducting solenoids separated by 506 mm. In 1980, the testing apparatus was completed and put into test, following ten years of arduous efforts. Although the technical specifications were not high at the time of completion, the development process of such an integrated engineering device involving superconducting and cryogenic technologies has not only accumulated a great deal of valuable experience and lessons, but also stimulated the overall development of cryogenic and superconducting technology in China.

In 1973, based on the plan of developing a proton synchrotron for high-energy physics research, the Institute of Electrical Engineering, CAS (IEE, CAS) began to develop superconducting dipole magnets for the accelerator and a superconducting magnet for high-energy detector. They wound two dipole magnets utilizing superconducting NbTi wires developed by Baoji Research Institute for Nonferrous Metals [1,3], and developed two cryogenically stable superconducting magnets with inner diameter of 10 cm and 35 cm [1,4]. Although this research was terminated due to the change of original plan, it gave an impetus to the development of NbTi superconducting wire in China.

In 1975, the CAS three institutions, the Institute of Electrical Engineering, Beijing Observatory and the Institute of Electronics worked together to develop a high-uniformity superconducting magnet for magnetic focusing in astronomical telescope. This magnet, operated in the persistent-current mode through a superconducting switch, achieved a spectral line resolution of better than 1.5 μm in the whole working range when experimenting together with the astronomical telescope [5].

At the same time, Chinese scientists also conducted research on superconducting magnet systems for a variety of different kinds of applications such as magnetohydrodynamic (MHD) power generation, Tokamak device used for nuclear fusion research, superconducting magnetic separation, superconducting motor, *etc*.

Specifically, in 1976 the IEE, CAS, conducted research on superconducting magnet for MHD power generation. As a result, they designed, developed and tested three superconducting saddle magnet models. Furthermore, they also conducted a series of studies on D-shaped superconducting model coils with the aim to construct a small-sized superconducting Tokamak [6].

Since 1977, Beijing General Research Institute for Nonferrous Metals (GRINM), Peking University and the IEE, CAS, conducted research on superconducting magnetic separation technology. GRINM and Peking University developed a high-gradient magnetic separator with a magnetic field strength reaching 6T, and conducted magnetic mineral separation test on hematite. Peking University and Beijing Automation Research Institute also developed a superconducting magnetic separator with a diameter of 10 cm and a central magnetic field strength of about 5T, which was applied to magnetic separation of diamond gangue. The IEE, CAS, also developed successfully a laboratory superconducting high-gradient magnetic separation prototype and conducted research on kaoline clay purification and coal desulfurization [7,8].

During the same period, a number of institutions, including the Institute of

Electrical Engineering, the Institute of Physics, CAS, and Shanghai Institute of Nonferrous Metals, Peking University, Changsha Research Institute of Mining and Metallurgy, and Beijing General Research Institute for Nonferrous Metals carried out research on making superconducting NbTi and Nb_3Sn magnets for laboratory use. The 8 T magnets wound using multifilament NbTi superconducting wires made in China were constructed. The Nb_3Sn solenoid with an inner diameter of around 44 mm and magnetic field intensity up to 11 T was also wound with Nb_3Sn tape made by CVD and low-temperature diffusion technique developed in Changsha Research Institute of Mining and Metallurgy. The Physics Department of Peking University applied the low-temperature diffusion method to produce Nb_3Sn superconducting tape (with a width of both 2.5 and 5 mm) and subsequently made a magnet that had a inner diameter of 16.2 mm and central magnetic field reaching 10 T. This magnet was applied to magnetize permanent magnetic alloy. In 1988, Shanghai Institute of Metallurgy, CAS, made a 12 T NbTi-Nb_3Sn superconducting magnet that was later used for 2D electron gas study [8].

After 1980s, the application research on low-T_c superconducting magnets continued to focus primarily on utilization in industry, transportation, medicine, and on magnets for scientific research. Most of the projects included also the application development stage. During in this period, the IEE, CAS, successfully developed for MHD power generation a superconducting saddle magnet system with 690 mm inner diameter, a 4 T central magnetic field and 8.65 MJ stored magnetic energy [9], it is shown in Figure 1. They also developed an industrial prototype of superconducting magnetic separator for kaolin clay purification. The production capacity of the separator is defined to be about 3t/h of dry clay powder [10]. It is shown in Figure 2. Furthermore, a 14 T NbTi-Nb_3Sn superconducting magnet has been constructed and tested at the IEE, CAS (see Figure 3). In order to obtain higher magnet field, a pair of low-purity Holmium cores were inserted into the NbTi-Nb_3Sn magnet and obtained the center field of 17 T at 4.2 K [11].

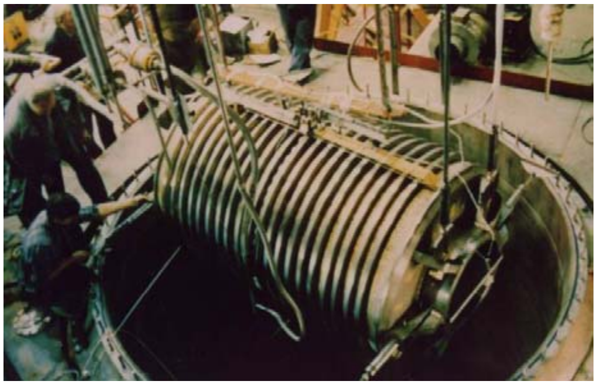

Fig. 1. A saddle superconducting magnet for MHD power generation.

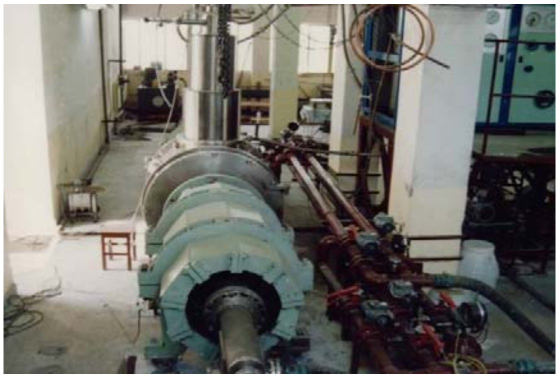

Fig. 2. Industrial prototype of 3 tons/h superconducting magnetic separator for kaoline clay purification.

Fig 3. A 14 T NbTi－Nb_3Sn superconducting magnet.

The Shanghai Power Plant Equipment Research Institute worked a long time for the development of superconducting synchronous generator. They developed and successfully tested a 400 kVA superconducting synchronous generator at the end of 1970’s. During 1980’s, they designed, developed and constructed a new 400-800 kVA superconducting synchronous generator based on their past achievements and performed several tests [12]. Since the middle of 1980s, Wuhan Marine Electrical Propulsion research Institute started a program to develop a superconducting homopolar machine. As a first stage, it was aimed at the construction of a 300 kW superconducting homopolar generator. They worked together with the IEE, CAS, and Zhejiang University conducting research on that homopolar machine. At the end of 1992, the machine shown in Figure 4 was tested; it reached nominal output power of 300 kW and operated stably [13].

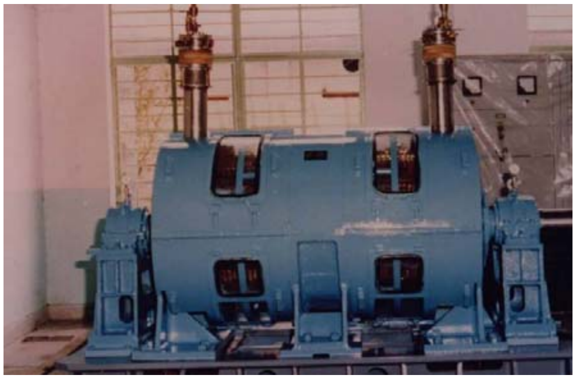

Fig.4. The 300 kW superconducting homopolar machine.

In the early 1990s, China Kejian Co., Ltd. in Shenzhen successfully developed a 0.6 T superconducting magnet system for magnetic resonance imaging (MRI). The MRI systems were then installed in hospitals located in Wuxi, Beijing and Shenzhen. They have also developed a 1 T MRI superconducting magnet system with LHe and LN_2 closed-loop refrigeration [14].

Some research institutions in China developed also superconducting magnets for scientific instruments in order to meet the requirements of various research experiments. For instance, Li Huanxing and others of China Southwestern Institute of Physics constructed a superconducting magnet for a 4 mm wavelength gyrotron, another superconducting magnet for a vibration sample magnetometer and an electromagnetic testing apparatus for characterization of superconducting materials. Zhang Yong and others of the IEE, CAS, also succeeded in developing magnet system for a 4 mm gyrotron and conducted research on magnets for a 200 MHz nuclear magnetic resonance (NMR) spectrometer, In addition, the IEE,CAS has made two sets of superconducting magnet systems for a GaAs crystal growth furnace [15].

In the early 1990s, the Institute of Plasma Physics, CAS, retrofitted the NbTi superconducting coil of a first-generation superconducting Tokamak reactor T-7 bestowed by the Kurchatov Atomic Institute of former Soviet Union, and established the China's first superconducting Tokamak experimental device HT-7 in Hefei [16]. Based on that, they proposed and build the Experimental Advanced Superconducting Tokamak (EAST), a larger, fully superconducting tokamak magnetic fusion energy experimental reactor with non-circular cross section. EAST contains 16 D shaped (3.52× 2.51m) superconducting toroidal coils with a major radius of 1.7 m and a toroidal field of 3.5T [17]. Figure 5 shows the general view of EAST. In September 2006, the system successfully conducted plasma discharge test and obtained high-temperature plasma of roughly 3 seconds duration. The plasma current exceeded 200 kA. EAST is still used for plasma studies. At present, the Institute of Plasma Physics, CAS, is undertaking several ITER-related tasks and is fabricating components under the ITER Procurement Arrangement. These tasks include: fabrication of superconducting conductors; design and fabrication of correction coils; design, fabrication and test of the magnet feeders that convey and regulate the cryogenic liquids, and connect electric power supply to the magnets.

Fig. 5. General view of the EAST experimental tokamak system.

Fig.6. High magnetic field conduction-cooled superconducting magnet having a warm bore diameter of 100 mm and generating center field of 10 T (IEEE, CAS).

In 1999, the Institute of Electrical Engineering and Cryogenic Technology Experimental Center, CAS, worked together to successfully develop a cryogen-free NbTi superconducting magnet system with a inner diameter of 50 mm and center field of 5 T which was directly cooled by a cryocooler [18]. This is the first superconducting magnet system of this type developed in China. After that, the IEE, CAS also successfully developed a conduction-cooled HTS superconducting magnetic separation magnet with the warm bore of 35 mm and magnetic field of 3.1 T. They also made a high-field and relatively large-bore cryogen-free superconducting magnet of 10 T with 100 mm warm bore diameter. The magnet, shown in Figure 6, consists of a 6T NbTi superconducting background magnet and a 4T Nb_3Sn superconducting magnet insert. The highest magnetic field it can generate is 10.3 T. For this conduction-cooled magnet, the overall temperature difference for different places across the whole superconducting coil is less than 0.1 K and the minimum operating temperature of the magnet reaches 3.6 K [19].

Based on the requirements for the upgrade of Beijing Electron Positron Collider, the Institute of High Energy Physics, CAS, proposed to build a superconducting NbTi magnet for the collider's spectrometer detector. The housing length of this magnet, shown in Figure7, is 4.91 m, the inner diameter is 2.75 m, the outer diameter 3.4 m. The superconducting coil is 3.52 m in length. The maximum field it can generate is 1 T and the maximum energy stored is 10 MJ with excitation current of 3,370 A. The magnet was successfully tested in 2007 [20]. On the base of this project, Zhu Zian and others of the Institute of High Energy Physics, CAS, worked together with Shandong Huate Company in 2008 to develop a superconducting magnetic de-ironing separator. The magnet bore size is 0.93 m and it can generate 3T magnetic field with stored energy of 3.4 MJ. The magnet itself is shown in Figure 8. At the specified lifting height 0.55 m, it produces the 0.432 T magnetic field for de-ironing.

Fig.7. Superconducting Magnet for Beijing Spectrometer Detector

Fig.8. Magnet of the superconducting de-ironing separator.

Since 2000, the IEE, CAS, has participated in the international cooperation project "Research on Alpha Magnetic Spectrometer (AMS)", led by Professor C.S. Ting, to collaborate on the 2nd generation detector (AMSC02) with superconducting magnet. The magnet is the key component of the spectrometer that, as a high-energy particle detector, is used to explore anti-matter, dark matter and the origin of cosmic rays in space. The IEE, CAS conducted research and development of the AMS02 magnet system using aluminum-stabilized superconducting wires. They have completed this magnet's quench safety evaluation, the scheme design of the gas supply system for the cryogenics of the magnet, the scheme design and test of other cryogenic system of the magnet. They proposed to use the conduction cooling technology to cool the superconducting magnet system for space exploration and performed the feasibility study. Meanwhile, they also conducted research on special cooling methods [19, 21].

In recent years, IEE, CAS also designed and completed a superconducting magnet system used in a gyrotron electron accelerator. The magnet is cryogen-free and consists of multiple uniform sections of magnetic field. This magnet can generate complicated magnetic field profile in the central region of 80 mm diameter. The highest field it can produce is 4.5 T and the uniformity is better than 10^{-3}. This system has been provided to users and is installed in a high-power microwave system. The IEE, CAS, also conducted research on the electromagnetic problems in magnetically navigated surgical operation system, and proposed a new superconducting spherical quadrupole magnet structure. Based on that, they have developed a model device for the above-mentioned magnetically navigated surgical operation, and conducted a series of simulated experiments. In addition, they also conducted research on inertia navigation. Furthermore, the IEE, CAS also successfully developed a 4T conduction cooled and solid-state nitrogen protected HTS magnet system with a bore size of 120 mm. The magnet was wound using HTS tapes. At present, the IEE, CAS, is also developing a 9.4 T MRI superconducting magnet with warm bore of 80 mm [19, 21].

In 2006, Institute of Cryogenics and Superconducting Technology, Harbin Institute of Technology and Lawrence Berkeley National Laboratory in USA undertook collaboratively the project of 'MICE Superconducting Coupling Magnet System'. This superconducting coupling solenoid magnet is made of NbTi superconducting coil that should generate magnetic fields of 2.6 T with current of 210 A. The coil inner diameter, length and thickness are 1,500 mm, 285 mm and 110 mm, respectively. The coupling magnet, cooled by a cryocooler is currently under development [22].

Presently, a 40 T hybrid magnet facility is under development at the High Magnetic Field Laboratory, CAS, in Hefei. The superconducting magnet made by Nb_3Sn and NbTi CICC with 580 mm room temperature bore size will generate 11 T magnetic field [23]

B. Large Scale Energy Applications

Power Transmision HTS Cables

The discovery of high-temperature superconductivity in 1986 has generated worldwide enthusiasm in the field of superconductivity research. Tremendous effort has been made towards application of high-temperature superconductors. In China, funding for applied research on high-temperature superconductivity became greatly strengthened.

Following the development of HTS tape conductors, research and development on HTS electrical systems was conducted during the Ninth Five-Year Plan (1996-2000) with a focus on power transmission cables and fault current limiters. In 1998, the IEE, CAS, worked together with the Northwest Institute for Nonferrous Metals Research and Beijing General Research Institute for Nonferrous Metals and successfully developed a HTS DC transmission cable model. It is 1m in length and can carry a current of 1,000 A at 77 K. In 2000, the three institutions worked together again and developed a 6 m long, 2 kA HTS DC transmission cable [24]. After that, under the support of the National 863 Program and CAS Knowledge Creation Project, and the support from domestic enterprises such as TBEA Co., Ltd, Xinjiang Branch and Gansu Changtong Cables Co., Ltd, the IEE, CAS, conducted successive studies related to the HTS power applications of high temperature superconductors. These include three-phase AC transmission cables, transformers, fault current limiters and SMES systems.

In August 2003, the IEE, CAS, successfully developed a 10 m long AC three-phase HTS cable of 10.5 kV/1.5 kA. In April 2004, Beijing Innopower Superconductor Cable Co., Ltd., successfully developed a 33 m long AC three-phase HTS transmission cable of 35kV/2kA, which was installed in Puji Substation in Yunnan Province for trial-operation (see Figure 9) [25]. In December 2004, the IEE, CAS, and Gansu Baiyin Changtong Cables Company in Baiyin city, Gansu Province worked together and successfully developed a 75 m long AC three-phase HTS transmission cable of 10.5kV/1.5kA, which was installed in Gansu Baiyin Changtong Cables Company and interconnected with the power grid in the company. (as shown in Figure10) [26]. In addition, the IEE, CAS, and Henan Zhongfu Industrial Co., Ltd in Henan Province have been developing jointly a 360 m long large current HTS DC cable with a current of 10 kA for aluminum electrolyze [27]. The cable has been installed on site (as shown in Figure 11) and is expected to be put into operation in 2012.

Fig.9. The 33m long, 35 kV/2.0kA HTS AC cable installed in Puji substation.

Fig.10. The 75m long 10.5 kV//1.5kA HTS AC cable installed in Baiyin Changtong Cables Company.

Fig.11. The 360m/10kA DC HTS cable under installation.

Superconducting Fault Current Limiters

In year 2000, the IEE, CAS, developed the first Chinese superconducting fault current limiter (SFCL) of 400V/25A. Following this accomplishment, they have proposed a number of different kinds of new principles for SFCL. In 2005, a 10.5kV/1.5kA bridge-circuited HTS SFCL with HTS coil, shown in Figure 12, was successfully developed. It was then installed in the Gaoxi substation of 110kV/10.5kV located in Hunan Province and performed demonstration operation for over 11,000 hours. In a three-phase-to-ground short circuit test of grid, the prospective fault current of 3.5 kA was successfully limited to 635 A at the pre-setup short-circuit point [28].

Fig.12. The 10.5kV/1.5kA SFCL installed at Loudi Substation.

Beijing Innopower Superconductor Cable Co., Ltd. developed a 35kV/90MVA saturated iron- core type SFCL and installed at Puji Substation in Yunnan Province in 2007(as shown in Figure 13). To verify its capacity in fault current limiting, the performance test was conducted in 2009 [29]. At present, a saturated iron-core type SFCL of 220kV/300MVA is developed by Innonpower, and IEE, CAS, is working to develop a 220 kV resistance type SFCL for practical power grid.

Fig.13. The 35kV/1.5kA core-saturated type SFCL at the Puji substation.

HTS Transformers

In 2003, the first 26 kVA HTS transformer in China was successfully developed by the IEE, CAS, and TBEA Co., Ltd, Xinjiang Branch. They worked together again and successfully developed a 630 kVA three-phase HTS transformer shown in Figure14 [30]. This transformer went through various tests and was interconnected with the power grid in TBEA Co., Ltd, Xinjiang Branch in 2005.

Fig.14. The 630 kVA three-phase HTS Transformer.

Other Grid Components, Integration

In 1995, the IEE, CAS successfully developed a 25kJ/5kW SMES device. Later, in 2004, a 100kJ/25kW SMES was made and put into experimental tests. At the end of 2010, the first 1MJ/0.5MVA HTS SMES system [31] was developed and was connected to a power distribution grid for trial-operation. It is shown in Figure 15. In 2005, Jiang Xiaohua and others of Tsinghua University successfully developed and testes a 500kJ/150kVA SMES system. In the mean time, Tang Yuejin and others of Huazhong University of Science & Technology successfully developed a 35kJ/7kVA miniaturized HTS SMES system which was applied in dynamic modeling of electrical power system.

In 2006, Tang Shaodong and others of Wuhan Marine Electrical Propulsion research Institute designed and constructed a 100 kW/500 rpm HTS homopolar-motor shown in Figure 16, which consisted of 6 racetrack HTS coils made by Innova Superconductor Technology Co.,Ltd. and operated under liquid neon temperature.

Fig.15. The 1MJ/0.5MW Superconducting Energy Storage Device.

Fig.16. The 100 kW HTS Motor.

At the beginning of 2011, the IEE, CAS, successfully completed integration and construction of a 10.5kV superconducting power substation incorporating a 75 m-long 10kV/1.5kA HTS power cable, a 10kV/1.5kA SFCL, a 10kV/0.4kV HTS transformer with capacity of 630kVA, and a 1MJ/0.5MVA SMES (as shown in Figure17). The substation, located at Baiyin National High-Tech Industrial Park, Gansu Province, has been put into trial-operation, providing electrical power of high reliability and quality to three high–tech enterprises in the area [32]. The successful development and operation of the superconducting power substation is a demonstration that the superconducting power technology would be a possible candidate for large-scale application in the future power grid which would be dominated by the renewable energy.

Fig.17. The 10.5kV Baiyin Superconducting Power Substation.

While carrying out applied research, the Chinese scientists also attach great importance to fundamental research on superconducting power technology. Supported by the National Basic Research Program of China (973 Program), National Natural Science Foundation of China and the CAS Knowledge Innovation Program, institutions like the IEE, CAS, have carried out application-related basic research on the electromagnetic physics basics of high temperature superconductors and the electromagnetic characteristics of HTS power devices. They studied the electromagnetic characteristics of HTS tapes and the stability problem of HTS magnets. These studies not only provide important knowledge during design and fabrication of the superconducting devices, but also help to explore new applications of superconducting magnets and other devices. For instance, based on these studies and also power electric technology, a number of novel designs for SFCL and for SFCL-SMES systems have been put forward [33].

III. RESEARCH ON SUPERCONDUCTING MATERIALS

A. Low Temperature Superconducting Materials

China began to develop low-temperature superconducting (LTS) materials NbZr and NbTi in 1964. At that time, the Institute of Physics, CAS, and Beijing General Research Institute of Nonferrous Metals (GRINM) took the lead in this regard, with the former focusing on the basic theory of materials while the latter focusing on material fabrication and production. Shortly before or after 1970, China began to develop Nb_3Sn tapes, using vapor deposition and diffusion methods, and multi-filament NbTi composite wire. Starting from 1972, the research on V_3Ga

material was also carried out. In the following years, other superconducting materials, such as Nb_3Ge, $Nb_3(Al,Ge)$ and $PbMo_5S_6$, were also studied [34,35].

In 1970, Baoji Institute for Nonferrous Metals (currently known as the Northwest Institute for Nonferrous Metals Research, NIN) developed and produced 1,800 kg NbTi/Cu mono-core superconducting composite wire for China Southwestern Institute of Physics to develop a plasma experimental apparatus consisting of superconducting magnetic plasma mirror. The wire section length was 5,000 m on average and 20,000 m for the longest. The critical current density was up to 1000 A/mm^2 (4.2K, 7.2 T). The performance of the wires was comparable with the commercial products made in other countries. In 1971, they also started research on NbTi/Cu multifilamentary composite wires [35].

In the early 1970s, Fang Junren and others of Changsha Research Institute of Mining and Metallurgy successfully produced Nb_3Sn tapes *via* both vapor deposition and diffusion methods. The critical current density for short samples (J_c) was up to $(2.5{\sim}2.7)\times10^3$ A/mm^2(4.2 K, 4 T). The value was close to those achieved internationally. The tapes had been used to wind superconducting magnets that could generate magnetic field up to 10~11 T. In 1972, Baoji Institute for Nonferrous Metals began to study the processing technique for preparing Nb_3Sn via bronze method. They were the first in China to wind superconducting Nb_3Sn magnets (9 T in magnetic field and 10 mm in bore size) using composite Nb_3Sn wires with over 1000 filaments [36]. During this period of time, GRINM investigated the material processing technology of V_3Ga and fabricated some conductors. The performance was comparable with that of materials made by ULVAC Japan, Ltd, and Furukawa Electric Co., Ltd [35].

In the early 1980s, China already had certain production capacity of NbTi superconducting materials. Based on statistics, 4 tons of various kinds of NbTi materials had been fabricated in China by 1982. The length of single NbTi wire made in China was already up to 20,000 m and the critical current density (J_c) for short samples of NbTi/Cu multi-filament composite wires was up to 3.5×10^3 A/mm^2 (4.2K, 5T). These figures were then on the advanced international level. At that time, the NbTi superconducting wires made in China had reached or exceeded performance of those made in other countries and yet had lower prices [37].

Starting from 1993, research on ultra-fine filament NbTi/CuNi-Cu composite wires was carried out. In 1995, Northwest Institute for Nonferrous Metals Research successfully developed ultra-fine filament superconducting composite wires with 1 μm thin filament, 0.17 mm outer diameter and nearly 1,000 m length. On this basis, they further reduced the filament size by introducing a Nb buffer layer. They have successfully developed superconducting NbTi composite wires with 0.46 μm thin filament and 24,462 filaments, suitable for AC applications. The critical current density (J_c) was 1.9×10^3 A/mm^2 (4.2K, 5T) [38].

The Northwest Institute for Nonferrous Metals Research had performed a great deal of development work on multi-filament Nb_3Sn composite wires using the bronze method. The fabricated wires exhibited a critical current density (J_c) value up to 9×10^2 A/mm^2 (4.2K, 10T) and 5.8×10^2 A/mm^2 (4.2K, 12T). In addition, they have conducted research on Ti-added Nb_3Sn superconducting flat tapes and twisted cable tapes. The J_c of these multi-filament composite tapes reached 3.7×10^2 A/mm^2 (4.2K, 20T) [39].

Meanwhile, the Shanghai Institute of Metallurgy developed Nb_3Sn multi-filament wires of various dimensions using the Ti-added niobium conduit method. The developed wires were utilized in winding a number of Nb_3Sn coils with different bore size, which were then used for making NbTi－Nb_3Sn superconducting magnets of 11 T～14 T [40].

GRINM conducted research on the fabrication of multifilamentary V_3Ga superconducting wire using the bronze method. They adopted a processing technique involving double hot extrusion of mono-core and then multi-core materials to obtain V_3Ga multifilamentary round wires. The wires, 1000 m in length, 0.5-1.0 mm in outer diameter and 10-20 mm in twist pitch, consisted of 100-1000 superconducting filaments of 10-30 μm size. These wires were tested by laboratories both in China and abroad. The J_c values were 2.7×10^3 A/mm^2 (4.2 K, 15 T) and 1.7×10^2 A/mm^2 (4.2 K, 21 T), reaching the world level. The V_3Ga long wire was used to wind a mixed 10T test magnet [35].

Since the discovery of high-temperature superconductivity in 1986, the major research teams shifted to HTS materials, and the research on LTS materials virtually came to a standstill. In 2003, however, this situation has been changed when the Northwest Institute for Nonferrous Metals Research and other organizations founded Western Superconducting Technologies Co., Ltd. The company is devoted to making conventional LTS materials for practical applications. Currently, it is the only manufacturer in the world that covers the whole-production process of LTS alloys from ingots, billets, bars, rods to wires. So far, the specialized production lines for titanium alloy and superconducting ingots, bars, rods and wires have been established. A yearly production capacity of 6,000 tons of cast ingots, 3,000 tons of rods, 400 tons of NbTi or Nb_3Sn LTS wires, and 100 tons of section bars [41]. At present, Western Superconducting Technologies Co., Ltd. has been certified by ITER Organization and ITER China as the company that is fully capable of manufacturing the superconducting wires for making ITER toroidal field (TF) and poloidal (PF) magnets. The company has signed a contract with ITER for manufacturing superconducting strands. In December 2010, ITER China, on behalf of ITER, signed with Western Superconducting Technologies Co., Ltd. a supply contract of 120 tons of superconducting strands for conductors of poloidal field, feeder and correction field coil.

B. High Temperature Superconducting Materials

The discovery of high-temperature superconductivity triggered worldwide research efforts in superconductivity research. Since 1990s, basic research, applied research and application development on high-temperature superconductivity have been progressing rapidly in the world. During the Eighth Five-Year Plan (1991-1995), Chinese researchers attached great importance to the fabrication technology of

Bi-based 2223 and 2212 phase superconducting conductors using the powder in silver tube approach. During the Ninth Five-Year Plan (1996-2000), Northwest Institute for Nonferrous Metals Research and GRINM fabricated Bi-based HTS multi-filament tapes with 19, 37, 61 and 85 filaments. For short samples, the maximum critical current reached 81 A (77K, self-field) corresponding the engineering critical current density (Je) of 7×10^3 A/mm^2. Northwest Institute for Nonferrous Metals Research had successfully developed 300 m long Bi-based superconducting tapes with a maximum critical current of 85 A (77K, self-field) corresponding to a engineering current density of 75 A/mm^2 [42]. At the end of 2001, Beijing Innova Superconductor Technology Co. Ltd commissioned a production line of Bi-based HTS tape with a yearly production capacity of 200 km. The critical current on the produced 100 m long tapes could reach 90A (77K, self-field) [43].

During the period of the Eighth and Ninth Five-Year Plan (1991-1995), GRINM, the Northwest Institute for Nonferrous Metals Research and the National Key Laboratory for Superconductivity affiliated with Institute of Physics, CAS, and the Shanghai Institute of Metallurgy, CAS, pursued active research on YBCO HTS bulk materials. The physical and chemical processes during the growth of single-domain YBCO bulk materials by the melt-textured method were investigated thoroughly. Based on these studies, a number of novel methods for the mass production of precursor powders were developed with intellectual property rights. These include the powder melting process (PMP) technique, sub-micron powder preparation method and the method of increasing pining centers by doping of various kinds of non-superconducting impurities and inclusions. Other technology issues related to the fabrication of YBCO bulk materials, such as seed-crystal preparation technique, method for oxygen propagation into large bulk samples, *etc*., were addressed. Growth technology for NdBCO bulk materials was also investigated [42].

In 1995, Jiao Yulei, Zheng Minghui, Xiao Ling and others from the Superconducting Material Research Center of GRINM adopted melting texture growth method (MTG) in combination with top-seeded SmBaCuO technique and successfully grew large-sized high performance yttrium-based (YBCO) bulk materials. For the bulk samples of 20 mm in diameter, the magnetic levitation force could reach 0.081 N/mm^2 (77K, 0.5T). In 1998, they successfully developed in China the first manned superconducting magnetic levitation demonstration system incorporating YBCO bulk materials made by them. The system was on display on many occasions. In 1999, they successfully made the first 100 kg superconducting magnetic levitation demonstration system in China, which was on display in Macau and Shenzhen. By 2000, GRINM had established the platform for research and fabrication of high performance YBCO HTS bulk materials, including facilities of powder preparation, bulk sample growth and test. The yearly fabrication capacity was between 500 to 800 pieces of 30 mm diameter YBCO bulk samples. The magnetic levitation force for over 70% of the fabricated bulk samples exceeds 0.095 N/mm^2 (77K, 0.5T), with the maximum reaching 0.151 N/mm^2. At present, for 50 mm diameter YBCO bulks fabricated by GRINM, the maximum magnetic levitation force has already reached 0.16 N/mm^2. The trapped magnetic field on the surface of bulk samples is up to 3.2 T at 50 K. The trapped magnetic field between two bulk samples at a spacing of 3 mm is up to 7.9 T at 30 K [42]. At the end of 2000, the Southwest Jiaotong University used 342 pieces of YBCO bulks provided by GRINM to successfully develop the first man-carrying HTS magnetic levitation test vehicle in the world shown in Figure 18. It could carry up to 4 persons. The vehicle was driven by a linear motor system and could move back and forth levitating about 25 cm over a 10 m long track [44].

Fig.18. First man-carrying HTS magnetic levitation experimental vehicle.

Based on the research on the YBCO bulk materials, Northwest Institute for Nonferrous Metals Research, in 2002, successfully developed the preparation technology of GdBaCuO bulk samples with the magnetic levitation force of 0.10 N/mm^2. It is believed that, because GBCO exhibits higher irreversible magnetic fields and higher critical current density under high magnetic fields as compared with YBCO, the GBCO may be more promising for applications [45].

In recent years, the superconducting YBCO coated conductors have drawn much attention. In China, research and development activities on coated conductors have been supported since mid 1990s. During the Ninth Five-Year Plan (1996-2000), developed was the method of fabricating cube textured nickel alloy substrate tape, required for the growth of superconducting YBCO conductors, using a orientation rolling technology. Using this method 1 m long cube textured nickel alloy tapes could be made. In the meantime, research on Ag substrate tapes and nonmagnetic textured Cu based alloy substrate tapes. In June 1996, Beijing University of Technology successfully prepared YBCO tape samples on c-axis oriented polycrystalline Ag substrates using PVD technique. The J_c of these tapes was 20 A/mm^2. In order to prepare strongly bound, dense, continuous and well textured buffer layers, they had investigated a variety of different buffer materials including CeO_2, YSZ and MgO, and developed a method of epitaxially growing cube textured NiO buffer layer via direct oxidation. A method of growing the second buffer layer by re-oxidation of surface was invented too [42].

During the Tenth Five-Year Plan (2001-2005), GRINM had prepared 10 m long YBCO coated conductor tapes. In 2011, Li Yijie and others of Shanghai Jiaotong

University successfully prepared long (on the order of 100 m) YBCO HTS coated conductors tape with the maximum critical current of up to 194 A/cm-width.

For practical applications, MgB_2 superconductors have attracted much attention due to their relatively high transition temperature and absence of weak links at grain boundaries. In the past 10 years, much progress has been made in China towards improving the performance of superconducting MgB_2 wires. Using the so-called powder-in-tube technique, Northwest Institute for Nonferrous Metals Research is capable to fabricate 1000 m long MgB_2 wires with high J_c. Using the wires, Northeast University in Shenyang has made a spilt MgB_2 magnet coil for open MRI [46]. They studied the doping effect of Ti, Zr and other elements on J_c and the upper critical field.

In 2006, the IEE, CAS fabricated MgB_2 superconducting wire with the addition of nano-sized carbon. The critical current density of 2×10^2 A/mm^2 (4.2 K, 10 T) was the highest reported J_c value in the world at that time [47]. The fabrication process was reproducible. They have also investigated the effect of doping by means of organic acids and their derivatives on the critical current of the wires, resulting in fabrication of high performance MgB_2 wires. In addition, by doping with C_{60}, the performance of MgB_2 wires was further improved, in particular, in high magnetic fields. At 4.2 K, J_c was more than 4×10^2 A/mm^2 in the 10 T field and 2×10^2 A/mm^2 in 12 T [48]. These values are comparable with those of NbTi superconducting wires at 4.2K. In 2007, they had produced 100 m long MgB_2 wires with good performance. The test results on a 103 m long and 1 mm thick MgB_2 wire doped with nano-sized carbon showed that the critical current was over 10^2 A/mm^2 (4.2K, 8T). The IEE, CAS, was the first in the world to apply the technology of heat treatment in strong magnetic field to the fabrication process of MgB_2 superconductor.

In the mean time, Peking University has studied the growth of a few or even tens of micron thick films on metallic substrates such as stainless steel, or thin filaments using HPCVD technique. In 2006, they have prepared 25 μ thick MgB_2 thin films on stainless steel substrates with J_c up to 3×10^4 A/mm^2 (4.2K) [42].

In 2008, superconductivity in iron-based superconductors has gained widespread attention. Shortly after the report by Japanese researchers on 26 K superconductivity in LaFeAsOF, Chinese researchers in the University of Science and Technology of China and in the Institute of Physics, CAS, discovered that superconductivity could be pushed above 40 or 50 K by replacing La with other rare-earth elements [49,50]. The transition temperature is thus higher than the McMillan limit based on the simple electron-phonon interaction model. Following this, the IEE, CAS first fabricated superconducting wires of iron-based superconductors using the powder-in-tube technique [51]. Through using Ag as sheath material, Ag or Pb as dopants, and ex-situ PIT process, they succeeded in improving transport critical currents of wires [52]. Recently, they have fabricated Fe-sheathed textured iron-based 122 superconducting tapes. At 4.2 K, the highest transport critical current densities J_c of 2.5×10^2 A/mm^2 (I_c = 180 A) in self-field and 35 A/mm^2 (I_c = 25.5 A) in 10 T have been achieved [53].From the Eighth Five-Year Plan (1991-1995), research on HTS thin films and superconducting junction preparation technology has been conducted in a number of institutions across the country. GRINM, Institute of Physics, CAS, and the University of Electronic Science and Technology of China worked on the preparation of YBCO thin films by (magnetron) sputtering and pulsed-laser-deposition (PLD) techniques. During the Ninth Five-Year Plan (1996-2000) and the Tenth Five-Year plan (2001-2005), the capability of preparing large-area double-sided YBCO films with a diameter of 2 inches was demonstrated. The typical performance of the films are as follows: $T_c \geq 89$ K (77 K, 0T), $J_c \geq 1\times10^4$A/mm^2 （77 K, 0 T）and the microwave resistance $R_s \leq 0.6$ mΩ (77K, 10GHz). Significant achievements had also been made in Tl-based and Hg-based HTS thin film preparation, which attracted international attention [54]. The films had been used for the fabrication of HTS microwave devices. In the meantime, the laser MBE technology and equipment was also developed and good progress was made in epitaxial growth of superconducting thin films on atomic scale.In 2002, Tianjin Hi-Tech Superconducting Electronic Technology Co., Ltd., was founded and conducted research on superconducting thin film preparation, wafer processing and components related to superconducting microwave filters. They applied a multi-source co-evaporation system from the German company THEVA to the preparation of double-sided HTS thin films with wafer dimension over 3 inches. At present, they can prepare 2-inch and 3-inch double-sided films for microwave device fabrication in a batch manner.

IV. RESEARCH ON SUPERCONDUCTING ELECTRONICS

A. Work Prior to 1986

The research and development on superconducting electronics in China started in 1960s. In 1965, the Institute of Physics, CAS, made a small cryotron array. Over the following 10 years they conducted research on superconducting gravimeter, superconducting receiving antenna and microwave parametric amplifier.

In 1970s and 1980s, research activities on superconducting electronics were carried out in many institutions across the country, including Nanjing University, Peking University, Fudan University, National Institute of Metrology, Changchun Institute of Geology, Chengdu Institute of Electronic Engineering, Hefei Institute of Cryogenic Electronics and Institute of Physics, CAS. The topics were mainly on metrology, SQUID and microwave device applications [55].

In 1980, Nanjing University (NJU) successfully made a Josephson junction mixer of 8 mm wavelength. It was made on a Nb point contact junction working at 4.2 K. The single sideband noise temperature was T_M~175 K and the conversion efficiency was 2.5 [56].

In 1985, National Institute of Metrology (led by Qiao Weichuan) and Fudan University (led by Qiu Jingwu) successfully developed Nb point contact RF SQUID magnetometer. The results from the National Institute of Metrology were transferred to Harbin Laser Instrumentation Factory for production. At the end of 1985, the Institute of Physics, CAS, Peking University and National Institute of Metrology successfully developed a RF SQUID magnetometer using the Nb/Si/Nb tunnel junction developed in Peking University [55]. In 1986, the Institute of Physics, CAS, successfully developed a DC SQUID magnetometer using Nb/Si/Nb edged tunnel junctions developed by them [57]

In 1986, University of Science and Technology of China together with South-Central Institute of Nationalities recorded magnetocardiogram (MCG) of human beings using a SHE dc SQUID magnetometer [58].

B. *Mixers and Detectors*

In 1998, Nanjing Purple Mountain Observatory, in collaboration with researchers in Japan, successfully developed SIS superconducting mixer receiver of 115 GHz, which was successfully installed on the 13.7-m millimeter-wave radio telescope of Purple Mountain Observatory operated near Delingha, Qinghai Province. It was upgraded into a 3-mm band 9-beam superconducting receiver [59,60]. The group is now working on the development of a superconducting array THz imaging system for China's Antarctic Dome A THz project.

Led by Prof. Wu Peiheng, NJU and National Institute of Metrology worked together on application of HTS harmonic mixing technology to quantum voltage standards. In addition, NJU also conducted research on application of HTS thin film oscillator to lock-in technology. They designed and made a FET oscillator of which the frequency was stabilized by a YBCO thin film micro-strip oscillator. [61]

Based on the research into NbN thin films and devices [62], Research Institute of Superconductor Electronics (RISE) at NJU, has started the design, fabrication and characterization of NbN HEBs from 2005 on[1]. The result for the double side band noise temperature T_N of about 1000 K at 2.5 THz, which is lower than 10 time of the quantum limit for the noise temperature, has been obtained in 2009 [63] and the operating frequency has been extended to 3.1 THz with T_N of about 1400 K [64] for an HEB with a bridge dimension of about 4 μm (width) ×0.4 μm (length) ×4 nm (thickness). To satisfy the requirements of practical detecting systems, the stability of the HEB detectors has been studied and improved. A feedback loop was introduced with a microwave source having a frequency much lower than the LO frequency at THz; the source output power could be adjusted easily. With feedback, Allan time of about 20 s was determined, compared to Allan time of about 1 s without the feedback loop [65]. By comparing experimental data with the quantum noise theory [64], it is believed that the performance of the detector can be further improved after optimization.

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[1] HEB is the acronym of hot electron bolometer.

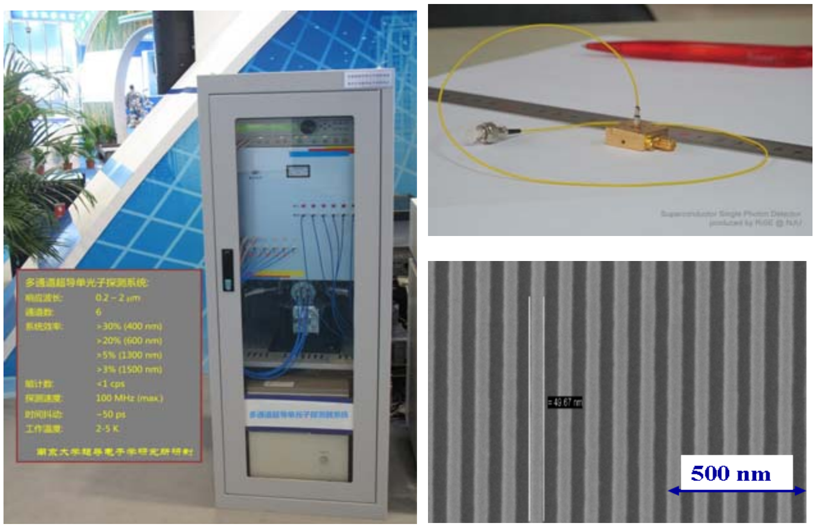

Fig.19. Superconducting single-photon detection system based on nanowire single photon. left) View of the system, upper right) mount of SNSPD, lower right) SEM image of fabricated SNSPD.

From around 2004, research on superconducting nanowire single-photon detectors (SNSPD) has been conducted. The Research Institute of Superconductor Electronics (RISE) of NJU has made SNSPD devices from the high quality NbN ultra-thin films made by them. After integrating with a cryocooler, the quantum efficiency of the detector system was around 6% and 3 % (at dark count rate: DCR~10/s) for 1310 nm and 1550 nm photons, respectively [66]. Figure 19 shows a photo of the integrated system deployed in quantum communication and quantum optics experiments. Similar research is also carried out at Shanghai Institute of Microsystems Information Technology.

C. Fabrication and Applications of SQUIDs

Since the discovery of HTS, the importance of applications of these materials in superconducting electronics was fully recognized in China. During the Eighth Five-Year Plan (1991-1995), the Institute of Physics, CAS, Peking University, Changchun Institute of Geology, National Institute of Metrology and Institute of Geophysical and Geochemical Exploration worked together on the fabrication of HTS SQUID magnetometers for the earth-field detection and performed field tests many times [67]. The Institute of Physics, CAS, Nankai University and former Nanjing 55th Research Institute of Ministry of Electronic Industry prepared DC SQUIDs using TlBaCaCuO thin films [68]. Peking University also conducted research on bi-crystal boundary junctions and directly-coupled DC SQUID devices. They also studied a new type of superconducting microstrip resonator for RF SQUIDs [69].

By 2000, Institute of Physics, CAS and Peking University had already fabricated HTS DC and RF SQUID devices for practical use. They made packaged sensors with related electronics. Peking University was able to fabricate RF SQUID sensors in small volume. The magnetic field sensitivity of the SQUID devices (better than 100 fT/Hz$^{1/2}$) was comparable to the products offered by other countries at that time.

Since 1990s, Peking University and the Institute of Physics, CAS, have used HTS SQUIDs to perform magnetocardiographic (MCG) measurements of both human beings and animals [70, 71]. In collaboration with Beijing China-Japan Friendship Hospital and using a single channel DC SQUID system, Professor Yang Qiansheng and others of the Institute of Physics, CAS, has performed 36 points MCG mapping measurements on over 100 healthy people and on some patients with heart disease. Mapping was done in a home-made simple magnetically-shielded room (MSR) which consists of a 2 mm thick μ-metal layer in addition to a 4 mm thick Cu layer and 10 mm thick soft-iron layer. By applying active compensation along the vertical direction, the residual magnetic field drift in MSR could be reduced to below 10 pT, providing a good environment for MCG measurements [72]. Recently, Ma Ping, Yang Tao, Dai Yuandong and others of Peking University have set up a 4 channel RF SQUID MCG measurement system in Beijing 309 Hospital.

In addition to MCG measurements, other research on application of HTS SQUID has been performed too. During the Ninth Five-Year plan (1996-2000), the Institute of Physics, CAS, conducted SQUID nondestructive test [73] and SQUID microscopy research [74]. Also, they have performed ultra-low field NMR and MRI experiments using HTS SQUID devices [75]. In 2011, they have demonstrated 2D MRI imaging at magnetic fields as low as 50 μT. Peking University has for many years worked together with the Institute of Geophysical and Geochemical Exploration and carried out geophysical measurements, particularly, transient electromagnetic measurements using HTS RF SQUIDs. Field experimental data showed that the SQUID sensor could provide information on 3 to 5 km deep underground, showing considerably better performance than that of conventional induction sensor.

After 1987, most of research on SQUID applications has been focused on using HTS SQUID devices. In recent years, Shanghai Institute of Microsystem and Information Technology, CAS, started to study the design, electronics and applications of SQUID sensors based on Nb junctions. In collaboration with the Juelich Research Center in Germany, they presented a DC SQUID readout circuit operating in the voltage bias mode, called SQUID Bootstrap Circuit (SBC) [76]. The simplified design is advantageous for multi-channel SQUID systems. Currently, they are developing a 64 channel DC SQUID MCG prototype following a 4 channel MCG system developed in 2010. It addition, they have studied ultra-low field NMR in unshielded environment by performing active compensation of the magnetic field variation [77].

D. Microwave Filters and Subsystems

Starting under the Eighth Five-Year Plan, research and development on a variety of different types of HTS microwave devices and related subsystems such as resonators, filters, delay lines, oscillators, antennas, superconducting-junction based mixers, *etc.*, has been pursued in China. The institutions involved include Nanjing University, University of Electronics and Technology of China, Tsinghua University, Institute of Physics, CAS, and Nanjing 55th Research Institute, Nankai University.

In 2003, Tsinghua University successfully developed an HTS filter for CDMA mobile telecommunication based on the earlier successful development of HTS filter for GSM1800 systems. In March 2004, an on-site test of HTS filter system was conducted in a CDMA mobile telecommunications base station of China Unicom Tangshan Branch, which was a great success [78]. The noise coefficient for superconducting filter system was only 0.8 dB, which was much lower than that of a conventional filter system. The steepness of band-edge increased one order of magnitude and out-off-band inhibition increased by more than 20 dB. After that superconducting filter system was installed, one of the key technical specifications – the transmitting power of mobile phone was reduced by 3.1 dB on average (*i.e.*, by more than 50%), and the reception sensitivity, coverage and quality of communication with the base station were greatly improved. Following the completion of this test, the filter system was permanently installed in the base station for long-term testing. It has been operating continuously for longer than three years, providing service to subscribers around the clock. In December 2005, Tsinghua University established a demonstration base for HTS mobile telecommunications application in the Big Bell Temple area of Beijing, in which there were five CDMA mobile telecommunications base stations for China Unicom [79]. These five stations applied 30-path superconducting filter system covering over 100,000 residents, which had been successfully and continuously operating for more than 6 years providing quality service to subscribers around the clock. The telecommunication performance was greatly enhanced, achieving the long-term and large-scale application in telecommunications field for HTS filter system (The above two achievements were the results of cooperation between Tsinghua and Prof. H. Piel's group of Cryoelectra GmbH, Germany). Figure 20 shows the superconducting filter system for CDMA mobile telecommunications base station while Figure 21 shows the photos of superconducting filter systems operating in various base stations in the frame of demonstration base for mobile telecommunications application in Beijing.

Fig.20. Superconducting Filter System for CDMA mobile telecommunications base station (Tsinghua Univ.)

In 2006, Zongyi Superconductor Technology Co., Ltd. was founded based on the superconducting filter technology developed by Tsinghua University. A production line with a yearly production capacity of 1,500 sets of HTS filter systems has been established in the Zhongguancun Science and Technology Park in Beijing. The company took three years to successfully develop the superconducting filter systems working in various harsh environments for dozens of applications, achieved very good results in various application tests. These accomplishments pave the way for mass production and widespread applications of superconducting filters.

The high sensitivity HTS UHF receiver front-end system, developed by the University of Electronic Science and Technology of China, successfully passed the trial operation test in the Digital Trunking Communication system in the early 2006 [80]. The results showed up to 6 dB improvement in the reception sensitivity and, thus, improved signal transmission quality. In 2006, Tianjin Hi-Tech Superconducting Electronic Technology Co., Ltd., the Institute of Physics, CAS, and Datang Telecom Technology Co., Ltd., worked together to successfully develop a HTS filter system for mobile communications. The prototype completed more than one-year field test operation without fault in a CDMA base station of Tianjin Telecom. At present, Tianjin Hi-Tech Superconducting Electronic Technology Co., Ltd. has the yearly production capacity of hundred sets of multi-path HTS filter system. The working frequency covers the range from 300 MHz to 30 GHz. The insertion loss is 0.2 dB.

Fig.21. Superconducting filter system operating in various base stations of the demonstration base for mobile telecommunications application in Beijing.

Apart from applications in mobile telecomunications, HTS microwave filters have been used in other systems. The Institute of Physics, CAS, developed the world first HTS meteorological radar front-end with the improvements in sensitivity of 3.7 dB and in anti-interference ability of 48.4 dB [81], which was demonstrated in a Radar Station in Beijing. 2006. A high-power-handling (11.7W) high-performance HTS filter was designed [82] and a microwave transceiver were constructed and successfully demonstrated in the 3G commercial network station of TD-SCDMA system with satisfactory results in 2009.

Aiming at satellite applications, The Institute of Physics, CAS, designed and fabricated an experimental HTS filter, which passed all the space qualification tests [83]. Subsequently, a microwave receiver front-end employing this filter had been constructed as a payload of the Chinese Experimental Satellite for New Technology. The satellite is planned for launch in 2012. The next HTS receiver system for space science research in the first Chinese Manned Space Laboratory is also being constructed.

Further applications of HTS filters in radio astronomy and wireless communications are also carried out. Unusually wide (60%) or narrow (0.3%) bandwidths and extremely high (K-band) or low (VHF band) frequency bands and high selective filters with group delay equalizations were successfully designed and fabricated [84].

During this period, Tsinghua University conducted research on superconducting antenna arrays based on large area thin film superconducting micro-strip, and developed a 2×2 four-unit antenna array. They also developed the 4.5 GHz YBCO circularly-polarized micro-strip antenna for space applications. The relative gain was increased by 3.1 dB as compared with normal metal (Ag) antenna.

E. Superconducting Qubits

From 2005, experimental work on superconducting qubits has been conducted in several institutions in China. Nanjing University measured the qubit signal, quantized energy levels and macroscopic resonant tunneling in the superconducting flux qubit based on RF SQUID. Under the microwave irradiation, they observed the photon assisted tunneling and Landau-Zener effect, which led to the strong population inversion and oscillation controlled by the microwave power [85]. This enables one to envision a micromaser based on macroscopic quantum transitions. They also investigated the microscopic two-level systems (TLSs) arising from the defects in qubit devices and their coupling with qubits. They took the advantage of the coupling between qubits and two TLSs to demonstrate coherent control in a solid-state tripartite qubit system [86].

The Institute of Physics, CAS, has been working on the fabrication and physical properties of superconducting qubit devices. They employed the tri-layer and double angle shadow evaporation techniques to fabricate sub-micron or nano-sized superconducting circuits with Josephson junctions. Using the devices made by them, coherent time evolution between two quantum states was observed on a cryogen-free dilution refrigerator [87].

V. CONCLUSIONS

During the past 50 years, the applied superconductivity research in China has progressed remarkably with continuous and strong support from Chinese government. In the areas of large scale applications, practical materials and electronics, many applications have been demonstrated. All of the progress has laid down a solid foundation for future development. In recent years, funding from non-government sources has been attracted to the research and development of applied superconductivity related projects. It is expected that applied superconductivity will further prosper in China.

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